Battery-powered current supply for superconductor measurements

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(Received 16 May 1988; accepted for publication 20 October 1988)

To measure the critical current of superconductors, a high output current supply is required. In addition to high current capability, the supply should be designed to reduce ground loop problems, respond linearly to an input control signal, and minimize output noise. A current supply with these qualifications has been constructed and tested. Although the supply was originally designed for testing conventional superconductors at high current levels, it has also been successfully used in measurements on the high-critical-temperature ceramic superconductors where the maximum current output was less than 1 A. The supply can produce 1000 A output current with a noise level of approximately 0.05 A peak-to-peak. The specifics of the current supply's design and performance are given.

INTRODUCTION

This current supply is an experimental design that has been gradually developed through continuous modification and improvement for an explicit application, critical-current measurements. These are extremely low-voltage measurements and, as such, they present special measurement problems. Specifically, the critical-current measurement requires a determination of the current level where the resistance of a superconducting sample becomes nonzero. In other words, a transition from zero voltage to finite voltage must be measured.[1] Consequently, small spurious voltages (such as those resulting from ground loops[2,3]), that might in some measurements be negligible, can become dominant in critical-current measurements. Also, current noise can result in a systematic error in the measured critical current or in completely random measurement results, depending on the noise level.[4] Finally, the inherent thermoelectric instability of a superconductor necessitates precise and stable current control. This instability also necessitates a sample protection device when operating at high current densities.[5] These concerns are reflected in the design of this current supply; however, specifics of the design should be considered quite flexible depending on the particular application. Although the only use for which this supply has been tested is superconductor measurement, the general elements of its design may be useful in many other applications.

I. CIRCUIT DESIGN AND PERFORMANCE

A. Input, control, and power stages

The basic circuit is a voltage-controlled current source (see Fig.1) consisting of three main stages: input, control, and power. The principal power source for the supply is a 4-V battery consisting of two 1500-A-h, 2-V wet cells. This 4-V battery supplies the output current through the power stage of the supply. Also, two 6-V wet cell batteries are used to power the control stage, and a 115-V ac-powered/ $\pm$ 15-V dc-output supply is used at the input stage of the supply circuit. The power stage of the circuit uses six Darlington transistor pairs in parallel, with each pair consisting of a 25-A (T3) and a 300-A (T4) power transistor. Each of the 300-A transistor emitters is connected to the positive bus bar through a separate 1-mΩ resistor. The resistors provide the required current-proportional feedback signals for the control stage. The collectors of these transistors are all connected to the 4-V battery through a single 1-mΩ current limiting resistor. The collectors of the 25-A transistors are all connected directly to the 4-V battery and the bases are each connected to a series combination of a 0.3-mH inductor and a 1-Ω resistor. These inductors and resistors are beneficial in stabilizing the circuit with respect to parasitic oscillation. The opposite ends of the inductors are connected together, forming a branch point. The emitter of another 25-A (T2) transistor is connected to this branch point and provides the current to drive the Darlington pairs. This transistor amplifies the output signal from the control circuit. A precision 0.1-mΩ resistor connected between the negative battery terminal and the negative bus bar provides a current-proportional voltage signal for measuring the total current output of the supply.

The control stage of the circuit is based on an operational amplifier (OA2) that compares the signal from the input stage with the feedback signal from the Darlington emitter resistors and applies the resulting signal to the power stage. In the feedback path, another operational amplifier (OA3) is used as a summing amplifier in order to combine and amplify the six signals from the feedback resistors. A trim potentiometer is used on this operational amplifier to allow adjustment of the control circuits bias point. Without this capability, one of two undesirable conditions may exist, depending on the offset voltages of the operational amplifiers in the control loop. These offset voltages may result in an offset current at zero input voltage, or they may result in excessive deadband (where a significant threshold input voltage is required to produce an output current), depending on the size and polarity of the offset voltages. The trim potentiometer can be used to correct either of these conditions. The potentiometer is adjusted so that a small deadband region exists at turn on. This adjustment ensures that there will be no offset current and that the deadband region is not excessive. In addition to providing a small margin of safety with respect to offset current, the residual deadband also masks any initial turn-on nonlinearity from the optically coupled input stage. In other words, the deadband prevents the sup-

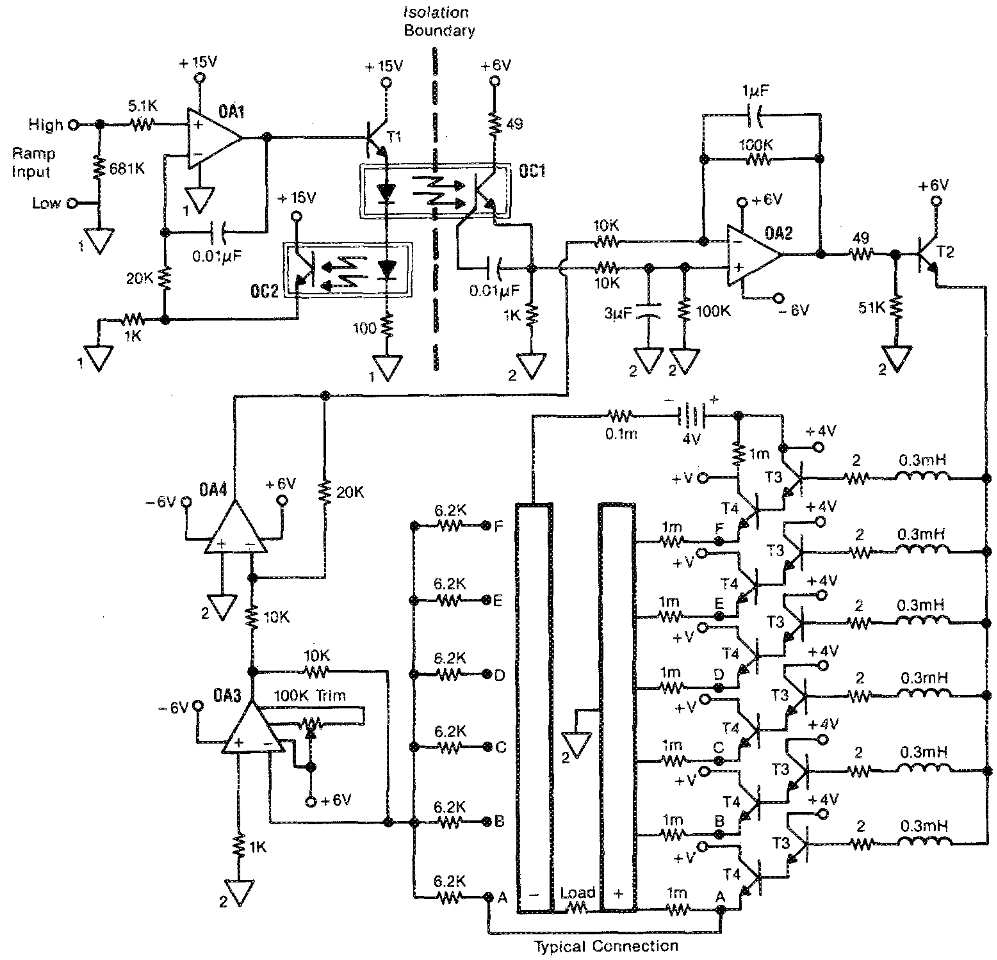

FIG. 1. Circuit diagram of the battery-powered current supply.

ply from responding to the input signal until the optical isolator is in its linear region. Since the summing amplifier inverts the feedback signal, another inverting amplifier (OA4) is required in the feedback path to restore the polarity of the signal. The resulting signal is then sent to the inverting input of the comparator. The comparator uses a feedback capacitor to reduce the ac gain and, thus, stabilize the circuit.

The main function of the input stage is to provide electrical isolation between the input signal generator and the supply circuit in order to avoid ground loop problems.[3] This isolation is achieved through the use of an optical isolator, or optocoupler (OC1). The input stage is linearized in a manner similar to that of the control stage. Again, a comparator (OA1) is used to compare the reference and feedback signals. The output signal from the comparator is amplified by a single transistor (T1). The feedback signal is supplied by a second optocoupler (OC2), which is in series with the first. This is necessary to provide electrical isolation. Moreover, the second optocoupler imitates the first and, thus, generates an appropriate feedback signal without electrically coupling the input and control stages. It is important to note that separate power supplies are used on each side of the isolation boundary (vertical dashed line on circuit diagram). Again, this avoids electrical coupling of the stages. The feed-forward optocoupler (OC1) was found to be a significant noise source because of an unused base terminal which was picking up 60-Hz noise. This problem was greatly reduced by connecting the base terminal to the emitter terminal with a 0.1-μF capacitor. This treatment of the feedback optocoupler (OC2) resulted in oscillation; consequently, the capacitor was omitted on this optocoupler.

B. Supply protection

The battery powered current supply was not designed for continuous operation at its maximum current level. Its duty cycle is limited by the maximum power dissipation of the 300-A output transistors and the 1-mΩ collector resistor of Fig. 1. Consequently, a method of overcurrent protection that uses thermal cutoff switches on both the collector resistor and the output transistors has been designed. For redundancy, two of the output transistors are monitored with cutoff switches, and two cutoff switches are used on the collector resistor. The four cutoff switches are placed in series with the coil of a 12-V relay and with the two 6-V batteries. Under normal operating conditions, the thermal cutoff switches are in the closed position. This, in turn, holds the 12-V relay in a position that connects the Darlington output stage to the control signal amplifier, T2. If the temperature of any of the four thermal cutoffs exceeds its set point, the relay current is interrupted and the relay switches the Darlington input point from T2 to common, which results in an interruption of the output current. After sufficient cooling, the thermal cutoff switches may be manually reset. The maximum current output of the supply depends on many factors including load resistance, duty cycle, and the available cooling for the output transistors. Consequently, the output capability of the supply and the specifics of the protection system will vary from one application to another.

C. Performance

The observed performance of the circuit with respect to output capability, linearity, current drift, and noise are described. The maximum current output of the supply in this particular application is approximately 1000 A. The linearity of the circuits' response was measured by comparing the current supply output with the control signal input. In this case, the input signal was a linear ramp. The results of this measurement are shown in Fig. 2 where the difference between the actual output current and the ideal linear current (DELTA I) is plotted versus the dc output current (CURRENT). This plot was constructed by generating a linear fit equation from the curve of input–voltage versus output–current in its most linear region. The ideal linear current was calculated from this equation and compared with the measured current over the entire input–voltage range. This plot shows that the difference between the ideal and actual currents is less than 1 A for current output levels between 50–400 A. At the maximum output of 1000 A the difference is approximately 30 A. Linearity measurements were made under a number of different conditions and these data are typical. Although this plot has been scaled to accentuate the deviation from linearity, the maximum nonlinearity represents only 3% of the measured output current.

For this application of the current supply, this level of nonlinearity is acceptable. However, for an application where a higher level of linearity is required, several elements of the present design should be considered. First, linearity of the input stage depends on a constant ratio of the large-signal current gains of the two optocouplers (OC1 and OC2). Careful matching of these two optocouplers can enhance the

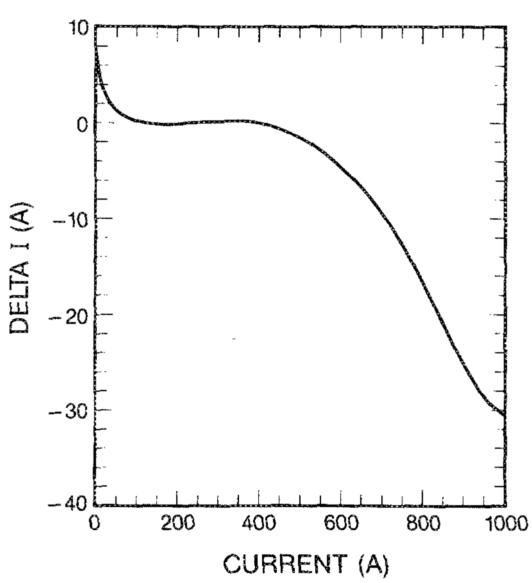

FIG. 2. Plot of the difference between the actual output current and the ideal linear current vs the dc output current.

linearity of the supply's response. Also, the comparator of the control circuit (OA2) results in a nonlinearity due to its closed-loop configuration. Moreover, the comparator is configured as an inverting amplifier in order to limit the gain of the offset-trim signal; however, this results in an impedance reduction at the inverting input. As a result, loading of the feedback signal by the 10-kΩ input resistor can reduce the supply's linearity. A reduction of this resistance can reduce this nonlinearity but an increase in the offset-trim level will also result. Finally, because the feedback signal is a sum of the signals generated by six different resistors and Darlington pairs, linearity depends on perfect matching of the resistors or consistent current sharing among the transistors. The former is more easily achieved; thus, both the 1-mΩ emitter resistors and the 6.2-kΩ summing resistors should be closely matched to enhance linearity.

The current drift of the supply was measured at two nominal current levels, 50 and 200 A. In both cases, the input signal was increased until the nominal current output was reached and then held constant until the end of the test. The input signal and the output current were continuously recorded during the test, which had a total duration of 30 min. For the 50-A test the current output increased by 0.30% after 1 min and by 2.1% after 30 min. At 200 A, the current increased by 0.18% after 1 min and by 0.78% after 30 min. Several tests were conducted with different load resistances, and these results are typical of all the tests. Also, drift measurements were made under varying initial temperature conditions. These tests suggest that the current drift is thermally induced. For example, when the supply is at ambient temperature at the beginning of the test, the current drifts upward with time regardless of the nominal current output. However, if a 200-A test is conducted immediately before a 50-A test, the current drifts downward during the 50-A test as the supply temperature decreases. As evidenced by these data, a disproportionate amount of the total current drift occurs in the first minute of the test. Drift measurements that isolated the input stage's contribution to the total current drift were made. These tests showed that the initial current drift was due primarily to the input stage. This condition might be improved by closer matching of the optocouplers, and it could certainly be improved by omitting the optically coupled input stage from the design in applications where ground loops are not a problem.

The supply's performance, with respect to output noise, was tested with two load resistances. In the first case, a low-inductance, 50-mΩ load (twisted wire) was used. This relatively large load resistance limited the output current to 20 A, but it also resulted in a sufficiently large current-proportional voltage signal for accurate measurement of the current ripple. The peak-to-peak current ripple was 0.01 A at 20-A output current. In the second case, a load resistance on the order of 1 mΩ was used to allow the supply to be operated at high currents. The voltage signal from a 0.1-mΩ resistor was used to measure the current ripple. For this case, the measured peak-to-peak current ripple was about 0.05 A for output currents from 10 to 900 A. The actual current ripple may be less than this, but, because of residual voltage amplifier noise, this was the limit of this measurement.

II. DISCUSSION

Although this design has proven very successful in this particular application, many of its elements can be changed or even deleted in order to better suit a different application. For example, in some critical-current measurement systems ground loops are not a problem and, consequently, the optically coupled input stage might be omitted in order to increase the circuits linearity while decreasing its complexity. Reference 2 gives specific test methods for evaluating critical-current measurement systems. For critical-current measurements the resistance of the current supply's load (a superconductor and connecting cables) is extremely low, thus allowing the relatively low voltage of the main battery. This low battery voltage would limit the current output for a resistive load. In this case, a higher voltage battery would be required in order to maintain the supply's output capability.

A disadvantage of a battery-powered current supply is that the batteries require periodic recharging. Furthermore, if the system is used on a daily basis at high output levels, regular overnight recharging is required. These conditions lead to the danger of overcharging. Consequently, the power supply that is used for battery charging is outfitted with two adjustable 1-to-10-h timers. Because the supply is usually unattended during recharging, two timers are used to provide redundancy. In this system both timers must malfunction in order for the batteries to continue charging beyond the selected time. Originally, lead-antimony batteries were used in this supply, but they have since been replaced with lead–calcium batteries. The calcium batteries do not generate as much hydrogen and oxygen gas when charging and, as a consequence, they do not require the maintenance or present the fire hazard that conventional batteries do. However, when overcharged, the lead–calcium batteries exhibit electrolyte swelling, which presents the danger of acid overflow.

Generally speaking, low-level measurement systems require low-noise power supplies. This is the main benefit of a battery-powered supply as compared to conventional high current supplies. Also, a battery-powered supply offers very high ground isolation, which is crucial in some systems. For any application, the supply's relatively simple design and versatility are important benefits. In many cases, the benefits of a battery-powered supply outweigh its minor disadvantages.

ACKNOWLEDGMENTS

The authors extend their thanks to E. S. Pittman for assistance with the linearized optocouplers, to R. M. Folsom for creating circuit diagrams, and to H. E. Spilman for circuit testing. This research was supported in part by the U.S. Department of Energy through the Office of Fusion Energy and the Division of High Energy Physics.

APPENDIX: COMPONENT DESCRIPTIONS

An effort was made to avoid the identification of commercial products by the manufacturer's name or number, but in some cases these products might be indirectly identified. In no instance does this identification imply endorsement by the National Bureau of Standards, nor does it imply that the particular products are necessarily the best available for that purpose.

All of the resistors used in this circuit are 1/8 W, 1%, metal–film resistors, except the 1 and 0.1 mΩ resistors, which are high current and low-temperature-coefficient resistors. All the capacitors are ceramic. The inductors are made from No. 18 insulated wire, wound on ferrite cores. The 4 V battery is two 2 V, 1500 A-h, lead–calcium wet cells wired in series. The 6 V batteries are 8 A-h rechargeable wet cells. The 15 V supply is a 115 V ac input, 25 mA output, commercial supply. OA1 is a number 3140 operational amplifier; OA2 and OA4 are number 741 operational amplifiers; and OA3 is a number OP5 operational amplifier. The optical isolators, OC1 and OC2, are both number 4N25. The transistor T1 is a 2N3904; T2 and T3 are TIP35 transistors. The output transistors, T4, are 500 A/300 A (peak collector current/dc collector current), 625 W/400 W (25 °C/100 °C) power transistors.

[1]L. F. Goodrich and F. R. Fickett, Cryogenics **22**, 225 (1982).

[2]L. F. Goodrich *et al.*, National Bureau of Standards Internal Report 87-3066, 1987.

[3]Ralph Morrison, *Grounding and Shielding Techniques in Instrumentation* (Wiley, New York, 1977).

[4]L. F. Goodrich, S. L. Bray, and A. F. Clark, Adv. Cryog. Eng. **34**, 1019 (1988).

[5]W. P. Dube and L. F. Goodrich, Rev. Sci. Instrum. **57**, 680 (1986).